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Multipurpose Pressure Vessel Scanner and Photon Doppler Velocimetry

NASA'S JOHNSON SPACE CENTER WHITE SANDS TEST FACILITY

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Multipurpose Pressure Vessel Scanner and Photon Doppler Velocimetry

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Critical flight hardware typically undergoes a series of nondestructive evaluation methods to screen for defects before it is integrated into the flight system. Conventionally, pressure vessels have been inspected for flaws using a technique known as fluorescent dye penetrant, which is biased to inspector interpretation. An alternate method known as eddy current is automated and can detect small cracks better than dye penetrant. A new multipurpose pressure vessel scanner has been developed to perform internal and external eddy current scanning, laser profilometry, and thickness mapping on pressure vessels. Before this system can be implemented throughout industry, a probability of detection (POD) study needs to be performed to validate the system's eddy current crack/flaw capabilities. The POD sample set will consist of 6 flight-like metal pressure vessel liners with defects of known size. Preparation for the POD includes sample set fabrication, system operation, procedure development, and eddy current settings optimization. For this, collaborating with subject matter experts was required. This technical paper details the preparation activities leading up to the POD study currently scheduled for winter 2015/2016. Once validated, this system will be a proven innovation for increasing the safety and reliability of necessary flight hardware.

Additionally, testing of frangible joint requires Photon Doppler Velocimetry (PDV) and Digital Image Correlation instrumentation. There is often noise associated with PDV data, which necessitates a frequency modulation (FM) signal-to-noise pre-test. Generally, FM radio works by varying the carrier frequency and mixing it with a fixed frequency source, creating a beat frequency which is represented by audio frequency that can be heard between about 20 to 20,000 Hz. Similarly, PDV reflects a shifted frequency (a phenomenon known as the Doppler Effect) from a moving source and mixes it with a fixed source frequency, which results in a beat frequency. However, for PDV, discerning the signal from the noise is difficult without a moving source to induce the modulation. A rotating wheel is currently being used as the moving source but its configuration is impractical and has cumbersome placement inside the current frangible joint test cell. As a way to combat this problem and verify a satisfactory signal-to-noise ratio, a reflective moving crystal piezo will be used to modulate a beat frequency, and an absorptive target will be used to block the signal in order to determine any back reflection coming from the probe and discern the true signal-to noise ratio. The piezo will be mounted and inserted onto the test table on an extendable telescopic antenna grounded by a magnetic base in the test zone. This piezo configuration will be more compatible within the test zone and allow for easy removal of the disk following acceptable signal verification and prior to frangible joint tests.

Additionally, topics of what was learned and smaller tasks given at White Sands Test Facility (WSTF) will be discussed. All statements in this paper are newly gained knowledge of what I have learned, observed, and have done while at WSTF.

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Nomenclature

4C	=	4 channel
8C	=	8 channel
AO mod	=	Acoustal Optic Modulator
CAD	=	Computer Aided Design
COPV	=	Composite Overwrapped Pressure Vessel
DIC	=	Digital Image Correlation
DoD	=	Department of Defense
DOE	=	Design of Experiments
EC	=	eddy current
EDM	=	Electrical Discharge Machining
FJ	=	Frangible Joint
ISS	=	International Space Station
JSC	=	Johnson Space Center
MDF	=	Mild Detonating Fuse
MPVS	=	Multipurpose Pressure Vessel Scanner
MSFC	=	Marshall Space Flight Center
NASA	=	National Aeronautics and Space Administration
NDE	=	Nondestructive Evaluation
NESC	=	NASA Engineering and Safety Center
NORS	=	Nitrogen and Oxygen Recharge System
NRB	=	NESC Review Board
PDV	=	Photon Doppler Velocimetry
POD	=	Probability of Detection
RF	=	radio-frequency
TA	=	Test Article
TPS	=	Test Preparation Sheet
USN	=	United States Navy
WSTF	=	White Sands Test Facility

I. Introduction

During my internship at NASA's Johnson Space Center (JSC) White Sands Test Facility (WSTF), I developed nondestructive evaluation (NDE) skills and knowledge of aerospace hardware including of frangible joints (FJ) and composite overwrapped pressure vessels (COPVs); all of which are vital to the aerospace industry. My primary focus was on a new versatile COPV scanner that outperforms its predecessors. My second project was developing a mount for a Photon Doppler Velocimetry (PDV) signal verification check. Lastly, I gained knowledge of the site's processes and the behavior of COPVs through a course instructed by long-term NASA engineers. This technical paper assumes the reader is familiar with NDE techniques applied within the aerospace industry.

II. Multipurpose Pressure Vessel Scanner

The Multipurpose Pressure Vessel Scanner (MPVS) is the latest iteration of COPV scanners at WSTF (See Figure 1). It is a modified version of the scanner developed for the Nitrogen and Oxygen Recharge System (NORS) for the International Space Station (ISS) (see Appendices A&B). The MPVS scans COPVs and their liners internally and externally. It can perform thickness mapping and flaw detection with the use of interchangeable eddy current (EC) and laser profilometry probes. The novelty of the system is that it can scan COPV liners for flaws and thinning after they have been wrapped and autofrettaged; which previously, has been a long-term technical challenge for NASA. Autofrettage is a process applied to the COPVs in which the liner undergoes plastic yielding as a result of internal pressurization. Scanning for thinning after autofrettage is vital to ensuring their safety for integration on a flight vehicle.

Figure 1. MPVS. *MPVS shown mid-scan with a developmental liner installed.*

A. NDE on Pressure Vessels

Nondestructive inspection for surface breaking cracks in pressure vessels has conventionally been done using fluorescent dye penetrant inspections (See Figure 2). The dye penetrant method involves manually spraying dye on the pressure vessel surface then wiping it clean with a cloth. The inspector then sprays the surface with developer which draws the penetrant out from the cracks, leaving visible indications. Since this is an extensively human-operated task, this process is subject to a wide margin of error. Some critical flaws can be smaller than the human eye can detect, thus necessitating a need for a more sensitive and automated process for flaw detection. Recently, laser profilometry and EC have been used as alternative methods to detect anomalies such as cracks or buckles in COPV liners.

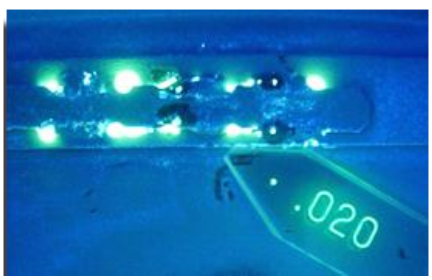

Figure 2. Dye Penetrant. *Weld cracks made visible by dye penetrant inspection method under black light.[1]*

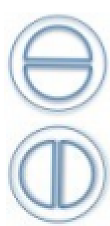

Figure 3. Coil Orientation. *For horizontal flaws there are two pickup coils spaced vertically, with the coil split along the horizontal axis. – For vertically-oriented flaws the coils are rotated 90 degrees.[2]*

Eddy current inspection is a predominantly automated process. It uses "dual coils for optimum detection of flaws with different orientation."[1] The technology works on the principle of electromagnetic induction and Faraday's Law, a subset of the Maxwell equations. An expanding and collapsing magnetic field forms in and around the coils after a pulsed magnetic field is provided by the driver coil. If the coil is placed on an electrically conductive material (i.e. an aluminum COPV liner), electromagnetic induction occurs and eddy currents are induced in the

material. The material generates its own magnetic field which opposes the coil's primary magnetic field.[2] A flaw in the material disrupts the eddy currents which is visible in the data collection process. Sensitivity of the eddy current method depends on the coil distance to the surface, orientation of the coils (See Figure 3), driving frequency and scan speed all of which can be optimized for flaw characteristics of interest.

B. Probability of Detection Study Definition and Preparation (My Role)

To apply this new system throughout NASA and the commercial space industry, a probability of detection (POD) study needs to be performed using the MPVS to quantify its capabilities. A POD study is a statistical analysis of the system's ability to find a flaw, miss a flaw, or incorrectly identify an inconsistency as a flaw. The POD study was requested by the NASA Engineering and Safety Center (NESC) and will be executed per the NESC plan entitled *COPV Liner Inspection Capability Development Assessment*. To perform the POD, a set of 6 tanks (COPV liners) containing various flaws of known size and location was produced. The flaw set consists of Electric Discharge Machining (EDM) notches and fatigue cracks grown through pressure cycling. The majority of the developmental details for the tanks occurred prior to the summer of 2015 following a Design of Experiments (DOE) written and approved by the NESC Review Board (NRB).

I supported the POD study development by primarily working with the Project Lead and EC expert to optimize instrumentation settings for the POD study inspectors. Following instructions documented in a draft Test Preparation Sheet (TPS), a mishap occurred when a command was used incorrectly to move the EC probe from the nulling point to the top of the liner, which resulted in crashing the probe into the liner surface and damaging both the probe and developmental test article. This indicated a need for clarity within the TPS. I took the responsibility of investigating the failure through a systematic root cause analysis by developing a fault tree. A root cause was found after communication with experts on the system. Resulting findings are provided within the investigative report.

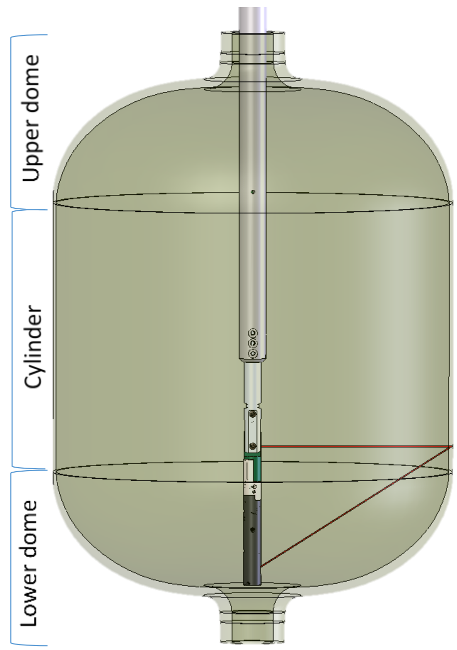

Figure 4. Liner Regions. *This image sections the 3 major regions of a COPV.*[2]

Once the mishap was resolved, I spent several additional weeks with the Lead Engineer operating the system and refining the TPS instructions while waiting on actual POD liners to arrive. Sample scans used a developmental tank with known flaw locations to optimize EC settings (i.e. rotation speed of the tank, drive frequency, data filters, etc). Scans were repeatedly performed over the same one inch section on the upper dome region (See Figure 4), but the data was inconsistent. At times flaws would show as a high voltage, but after taking scans under the same conditions flaws would have a significantly lower voltage, implying an issue with the system and/or probe. A number of system variables were adjusted and scans repeated in an attempt to identify the cause. Unfortunately due to my limited time at WSTF, I was not able to see the resolution of troubleshooting these issues.

III. Frangible Joint

Frangible joints (FJ) are used for clean separation between rocket stages (i.e. leaving no debris) (See Figure 4). Frangible Joints contain a stainless steel tube casing that encompasses a charge holder and a mild detonating fuse (MDF). An elastomeric charge holder holds the MDF as it transfers explosive energy into the tube which expands and fractures, separating the joint and the adjoining structures. In order to be used for human-rated launch vehicles, an assessment needed to be done to understand their sensitivities, risks, and reliabilities to ultimately provide confidence for their use in human-rated applications.

Figure 4. Example of frangible joint used for Max Launch Abort System. [4]

A. Data collection

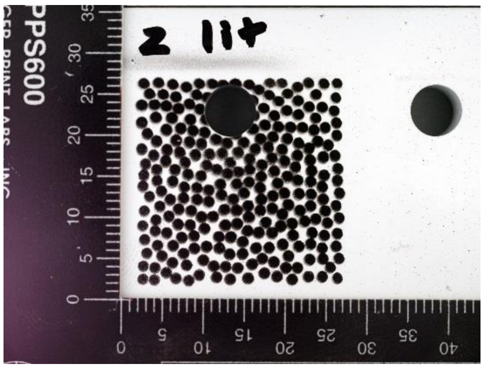

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Figure 5. DIC Dots. *High Resolution Image of DIC dot placement.*[5]

Digital Image Correlation (DIC) and Photon Doppler Velocimetry (PDV) are two of the primary methods for data collection during FJ tests. DIC is a 3D optical data collection method that uses high speed cameras to track dots placed on the test article (TA) that expand and contract during joint breakage (See Figure 5). PDV uses laser interferometry to extract the velocity of key location during joint separation.

A.1 PDV System Workings

The three PDV systems currently being used at WSTF include a 4 channel (4C) and two 8 channel (8C) systems. PDV data collection happens over a period of 1 ms, which is about the time it takes for the MDF to fracture the joint. A delay is built into the system after the initial trigger is sent to detonate the charge.

The 4C PDV system has two initializing devices within its series: radio frequency (RF) Driver and Fiber Laser. Both of these devices are inputted into the acoustal optic modulator (AO mod). The AO mod shifts and splits the Fiber Laser 90/10. The 90% is split into four channels corresponding to four different locations on the test article. The frequency is reflected off the test article and into a circulator that sends it to the receiver to be mixed with 10% of the original frequency. The fiber signal going into the black detector box is converted into an electrical signal and the recorded data is displayed on a Scope Box, designated *Scope 3* for the 4C system. To understand how the system works, I created a rough diagram detailing the flow of the system (See Appendix C).

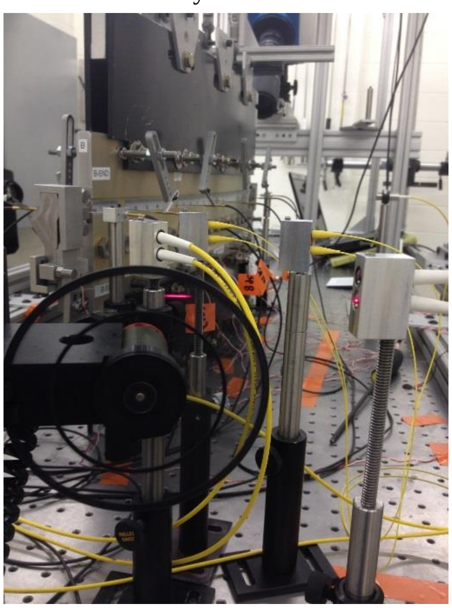

Figure 6. Black Spinning Chopper. *The chopper is in motion while the laser is being reflected off the inside moving surface.*[6]

The 8C PDV system has two lasers with different frequencies: one is a reference frequency (reference laser) and the other is the main frequency (main laser). There is no need for an RF Driver to shift and split the frequencies since there are two laser sources. Each laser is split 8 ways for 8 different locations on the TA. The reference laser goes directly into the detector, similar to the 10% frequency for the 4C system. The main laser reflects directly off the test article and is sent through a circulator. From this point, each system follows the same path to data collection. The main difference between these two systems is that the 8C system starts with two lasers and the 4C system has one laser that is shifted and split. I created a rough wire diagram detailing the 4C system (See Appendix C).

A.2 PDV Signal Verification (My Roll)

Currently there is not a signal verification method for the 4C or 8C systems in the current test bed. At the time of set up, the test article is not moving, so it is not known whether there is an issue with the PDV systems before an actual test. Conventionally, a rotating wheel known as a chopper has been used for the signal verification (See Figure 6). However, with a smaller test bed and more instrumentation, the large rotating chopper has become impractical for this type of use (See Figure 7). Because of this, there is a need for a smaller moving object that can be easily placed in and out of the test area.

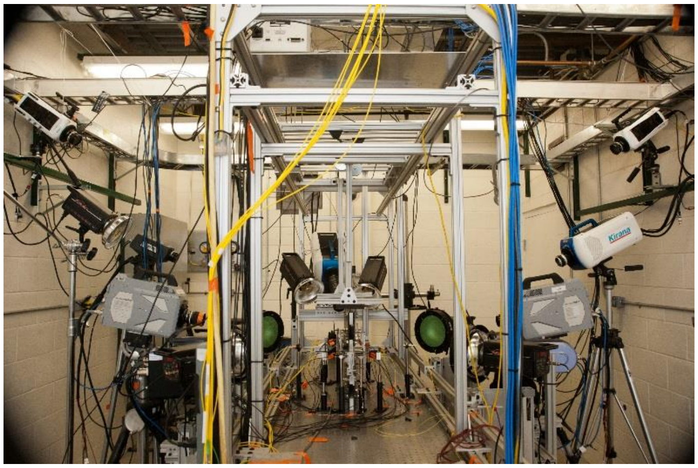

Figure 7. Frangible Joint Test Configuration. *Overview photo of the crowded test bed with cameras for DIC and lasers for PDV.*[6]

Using a piezoelectric (piezo) disk as the potential moving object, I designed a mount to easily extend into and out of the test area without interrupting the other instrumentation. A piezo disk uses the piezoelectric effect which is a reversible process for which certain materials move as a result of an applied electrical charge. By having this moving object as an intermediate verification step, the risk of having noisy or weak data for an actual FJ test can be avoided (See Figure 8).

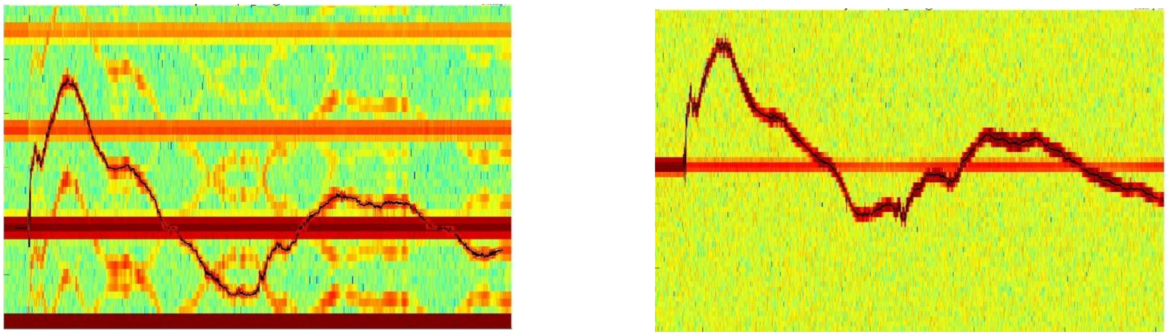

Figure 8. PDV Data. *The data on the left was taken during a FJ test and has a low signal-to-noise ratio. There is echoing in the background that signified a high laser power, and the data is difficult to distinguish across the baseline. This could have been recognized before the FJ test by recording data on a sample moving object. This data on the right was the result of troubleshooting the power issue with the data on the left. This data shows a high signal-to-noise ratio and an optimal reading of the data crossing over the baseline.*

Figure 9. PDV Mount. *This preliminary CAD shows a telescoping rod that is connected by a clamp-on-clamp fitting and grounded by a magnetic base. This assembly will suspend the moving object.at an optimal height and distance in front of the laser.*

The piezo disk is mounted on a telescoping mirror, which can extend up to 19.5 inches with just one telescoping attachment. The mount assembly has 6 degrees of freedom, giving it a full range of motion to be easily moved within the test bed (See Figure 9). Although this mount is versatile, the piezo disk still needs a practical power source. This is still being researched by the engineers at NASA.

IV. COPVs

Composite Overwrapped Pressure Vessels (COPVs) are a vital component used to hold liquids under pressure. They are crucial hardware needed for flight, as they provide fuel for life support and propellant systems. The use of COPVs provides significant weight-savings and safety assurance when compared to unwrapped pressure vessels, reducing flight costs and increasing payload size. Due to their importance, COPVs are consistently monitored for anomalies that can result in changes in their mechanical behavior, a main concern being stress rupture.

A. Inspection for Damage to COPVs NASA Course

During my time at WSTF, I took a Damage Detection Course taught by highly experienced NASA personnel. Damage to COPVs were a result of changes in its mechanical behavior due to various failure modes: stress rupture, etc. More information can be found in the Inspection for Damage to COPVs course booklet.

V. Reflection

A. NASA JSC White Sands Test Facility

During my time at NASA JSC White Sands Test Facility, I learned the 5 core capabilities of this site: Propulsion tests (engine system, attitude control at altitude, test stands), Oxygen Safety/Hazards, Hypervelocity, Propellants Hazards, and COPVs (what are the safety issues). Although capable of manufacturing aerospace quality components, WSTF focuses primarily on testing components to characterize performance and recognize safety hazards. In other words WSTF wants things to fail so they can see how they fail and implement safety protocols. The site mainly provides services to stakeholders including other NASA centers, Boeing, SpaceX, Virgin Galactic, the Department of Defense (DoD), United States Navy (USN), and etc.

The organization that I supported was RF111, which is composed of civil servants who work to manage the site's capabilities. The purpose of this organization is to support NASA's objectives through testing and evaluating materials and components in hazardous scenarios. My position as an intern included supporting the projects for which my mentor serves as Project Manager. These projects included two different NESC (NASA Engineering and Safety Center) Assessments: Frangible Joint and COPV Liner Inspection Capability Development Assessment.

B. Value

As an aerospace engineering major, this experience has given me an immense amount of practical knowledge. Having been trained by NASA personnel to operate the MPVS has been an invaluable experience that has exposed me to new instrumentation, new technology, and NASA processes at an early point in my career, which gives me a better idea of how I want to contribute. NDE is an important field of study to understand for someone who wants to be in the aerospace industry. On an aerospace scale, NDE is the middleman between development and flight-readiness for crucial flight hardware. On a larger scale, NDE is used to assure structural components and systems work as intended. Data collection for frangible joint is important for a detailed analysis of how the joint performs. These frangible joints are expected to be used on human-rated vehicles in the future, making these tests critical to provide factual evidence of their safety. I think this internship would be beneficial for all engineering disciplines. By focusing on EC NDE and the FJ data collection processes, I have a major advantage and insight on the future of aerospace engineering.

This experience surprised me in many ways. Coming from another NASA center, I immediately saw a different culture in the way things were ran at WSTF. One of the reasons I chose to take this opportunity is to get a different perspective within NASA. Being a smaller site, employees seemed to be busier, and juggling many different projects, whereas my previous tour at Marshall Space Flight Center (MSFC) had many experts in their field working on similar projects. My only disappointment is that I will not be able to perform the POD for the eddy current project, but I am fortunate to be part of the critical step that is preparing for this milestone. Still, with my limited time, experiences like these will always be invaluable.

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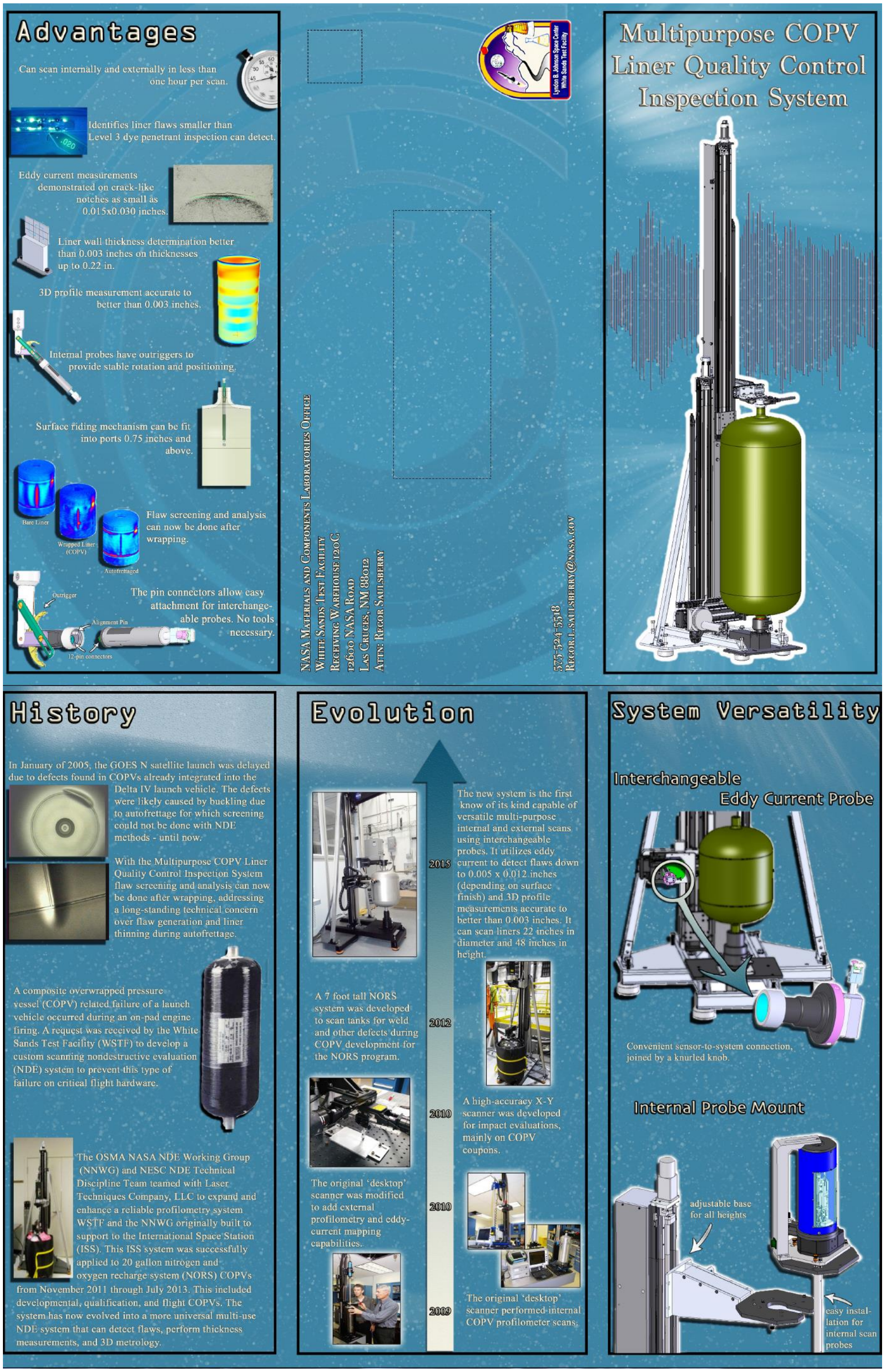
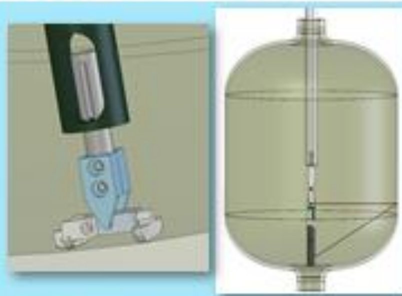
Appendix A: MPVS System Brochure Highlighting Capabilities



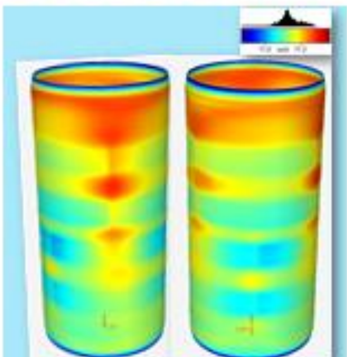
Appendix B: MPVS System Brochure Highlighting Capabilities

Multipurpose Pressure Vessel Scanner

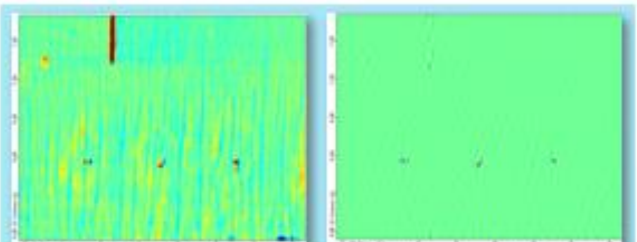
Multipurpose Pressure Vessel Scanner (MPVS). The image above depicts a 300 liter (L) COPV liner installed for NDE.



Eddy Current Probe (Left) and Laser Sensor in a 44L Liner (Right). A surface-riding assembly for the eddy current (EC) probe pivots as it moves along the contour of the liner in order to maintain cylinder and dome surface contact. The internal laser sensor also articulates and follows both the cylinder and dome.



3D Laser Profile of the outside diameter of a 380L liner.



Eddy Current Data. EC data of the inside diameter showing flaws before being processed (Left) and after being processed for noise reduction (Right). The flaw dimensions range from Width: 0.0009-0.0011" Depth: 0.0049-0.0058" Length: 0.0123-0.0127"

Project Overview

Following a composite overwrapped pressure vessel (COPV) related failure of a launch vehicle during an on-pad engine firing, a request was received by the White Sands Test Facility (WSTF) to develop a custom scanning nondestructive evaluation (NDE) system to help prevent this type of failure on critical flight hardware in the future. To support this, a more sensitive inspection method was needed to outperform conventional fluorescent dye penetrant in its flaw detection capabilities. The OSMA NASA NDE Working Group (NNWG) and NESC NDE Technical Discipline Team teamed with the Laser Technique's Company, LLC to expand and enhance a reliable profilometry system WSTF and the NNWG originally built to support to the International Space Station. The original system mapped the interior and exterior of COPV liners and vessels, giving radial measurements accurate to 0.003 inches, including ellipsoid heads. This system was successfully applied to the 20 gallon ISS nitrogen and oxygen recharge system (NORS) COPVs from November 2011 through July 2013, including developmental, qualifications and flight COPVs. The system has now been evolved and expanded into a more universal multi-use NDE system that can detect flaws, perform thickness measurements and 3D metrology.

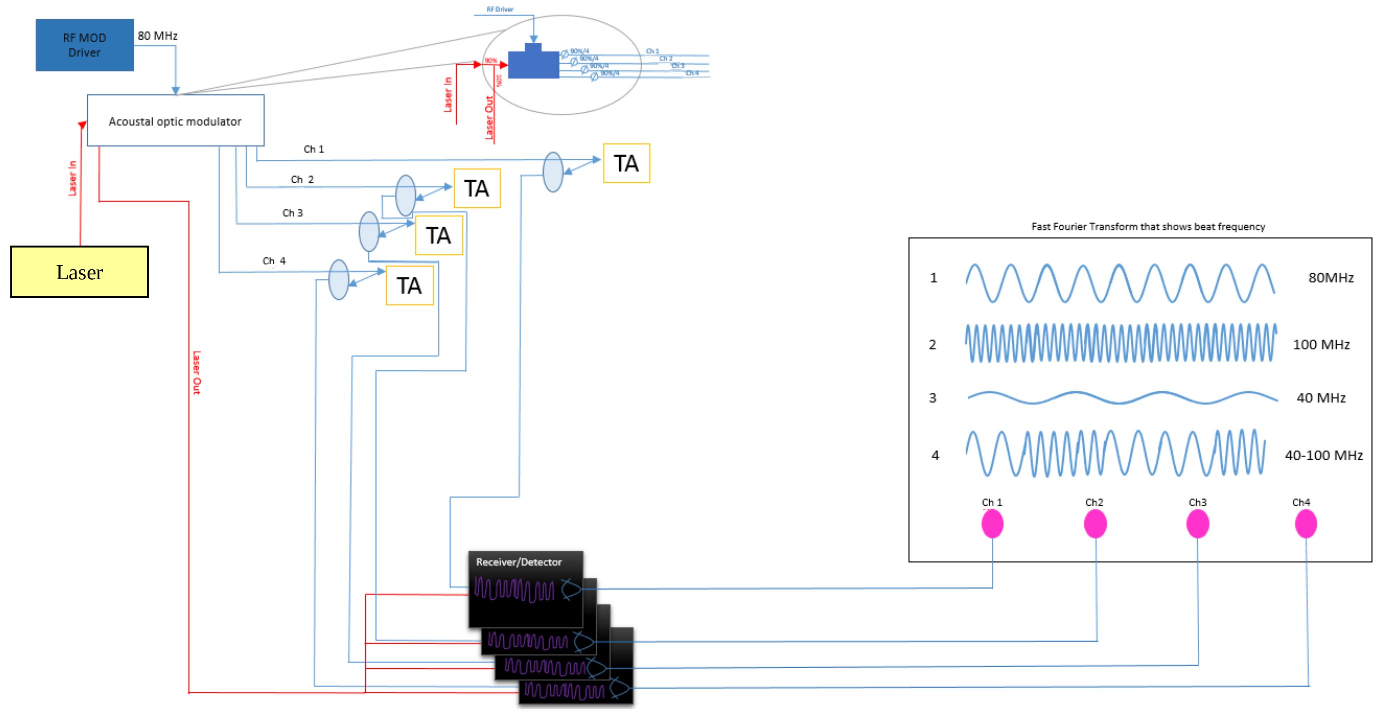
Novelty

This is the first know system capable of extremely versatile multi-purpose internal and external scans using interchangeable probes. Specifically, the MPVS utilizes eddy current and laser sensors for flaw detection, thickness mapping, and 3D profile measurements. It can detect flaws down to approximately 0.005 x 0.012 inches (depending on surface finish) and 3D profile measurements accurate to better than 0.003 inches. It is capable of scanning liners up to 22 inches in diameter and 48 inches in height. Flaw screening and analysis can now be done after wrapping, addressing a long standing technical concern over flaw generation and liner thinning during autofrettage.

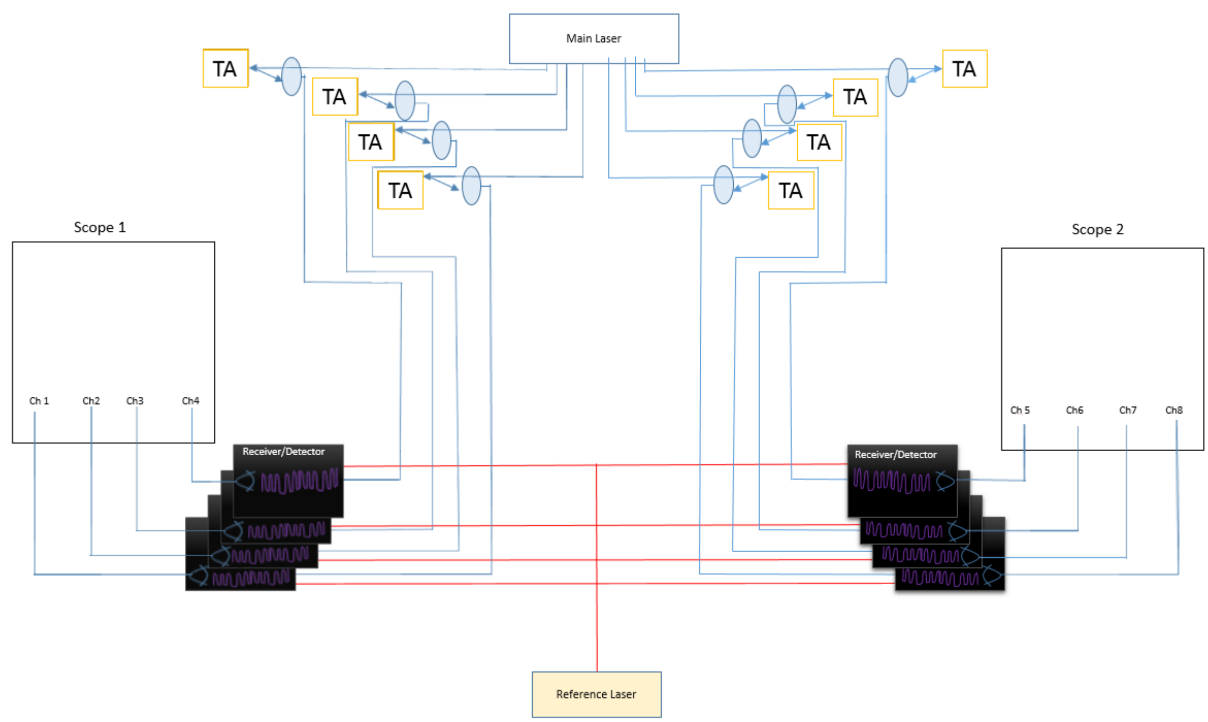
Outcome

An upcoming probability of detection (POD) study will validate the system's capabilities. It will produce "game changing" advancements concerning the safety and reliability of crucial flight hardware – COPVs.

Appendix B: MPVS System Brochure Highlighting Capabilities



4 Channel System Workings Diagram. *This diagram outlines the workings of the 4 channel system. There is one laser input that is split 90/10. The 90% goes to the 4 channels and the 10% is the reference beam. The resulting data waves shows what the data might look like if the test article is not moving (Ch1), moving towards the laser (Ch2), moving away from the laser (Ch3), or moving back and forth (Ch4).*



8 Channel System Working Diagram *This diagram shows the workings for the 8 channel system. There are two lasers for which one is the reference and the other is the main laser. The main laser is split 8 ways to reflect directly off the test article. The reference laser is mixed with the reflected light from the test article. The resulting beat frequency is displayed as data in scopes 1 and 2.*

Acknowledgments

The author would like to thank her mentor, Regor Saulsberry, for giving her this incredible opportunity to work on these innovative and highly technical projects. She would also like to thank Ralph Lucero and Charles Nichols at White Sands Test Facility for training her on the Multipurpose Pressure Vessel Scanner and Tim Gallus for explaining the Photon Doppler Velocimetry system.

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